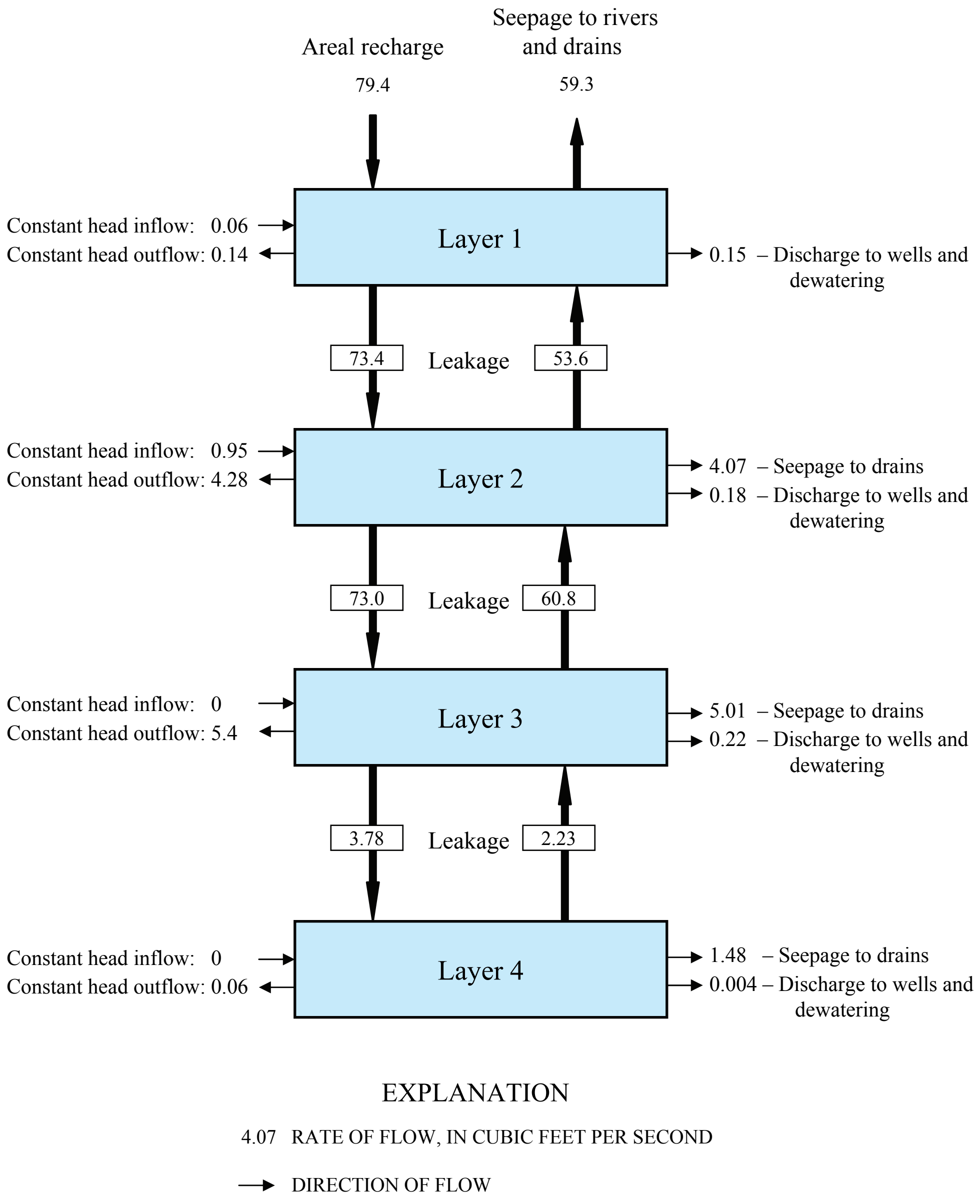


Figure 28. Distribution of water-budget components among the layers of the digital flow model for the Arnold Air Force Base area.

Ground-Water Withdrawal Wells Particle Tracking

Currently (2005), ground-water withdrawal wells are operating at SWMU 1&2, SWMU 5, SWMU 8, and SWMU 10. Particle-tracking results from these SWMUs under conditions with the ground-water withdrawal wells pumping show that no particles leave the SWMUs (fig. 32).

In 2005, five new ground-water withdrawal wells along the airfield road were scheduled to begin pumping. To analyze the effect of these new wells on the flowpaths from SWMU 1&2, a particle-tracking simulation was performed with the existing ground-water withdrawal wells at SWMU 1&2 turned off and the new wells along the airfield road turned on. The airfield road ground-water withdrawal wells and the J4 test cell capture about 89 percent of the particles from SWMU 1&2, with about 11 percent of the particles discharging near Rutledge Falls (fig. 33). To estimate the travel time of ground water from the area near the airfield road ground-water withdrawal wells to Big Spring at Rutledge Falls, a simulation was performed starting particles just downgradient of the capture area of the airfield road withdrawal wells. The estimate of travel time from the airfield road withdrawal wells area to Big Spring at Rutledge Falls ranges from 1 to 5 years with a mean travel time of 2 years and a median travel time of 2 years. This mean travel time of 2 years from the airfield road area to Big Spring at Rutledge Falls, compared with the mean travel time of 46 years from SWMU 1&2 to Big Spring at Rutledge Falls implies that the airfield road withdrawal wells should substantially reduce the time required to observe a change in contaminant discharge from the “northwest plume” at Big Spring at Rutledge Falls.

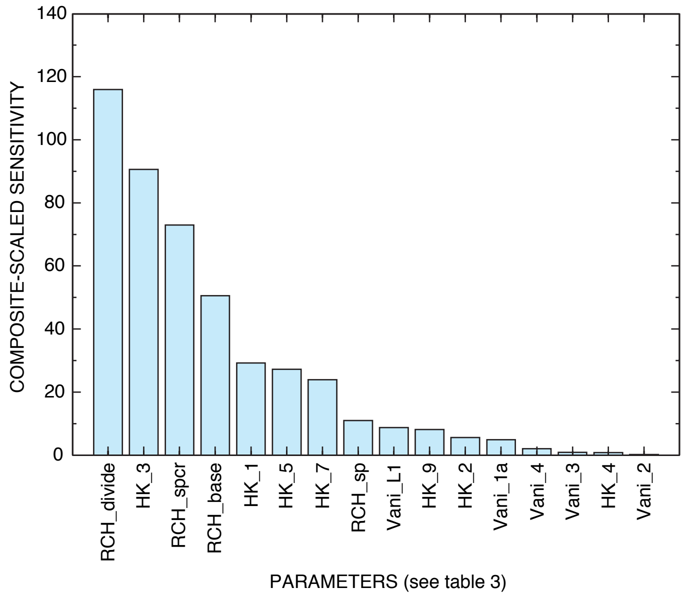


Figure 29. Composite-scaled sensitivities for model parameters.

Dewatering Facilities Particle Tracking

Three particle-tracking simulations were run to analyze the effects of dewatering facilities on flow paths in the Main Test Area (MTA). In the first simulation, particles were placed in the MTA (in a rectangular area bounded by Third and Fifth Streets and Avenues C and E) and tracked forward under conditions with all dewatering facilities turned on (fig. 34). In the second simulation, particles were placed in the MTA and tracked forward under conditions with all dewatering facilities turned off (fig. 35). In the third simulation, particles were placed at the location of the dewatering facilities and tracked backwards to their recharge locations (fig. 36). These simulations illustrate that the dewatering facilities have a substantial effect on flow paths that were simulated from the MTA and are effective in containing most of the ground water in this area.

Model Limitations

Models, by their very nature, are simplifications of the natural system. Factors that affect how well a model represents the natural system include the model scale; inaccuracies in estimating hydraulic properties; inaccurate or poorly defined boundary conditions; and the accuracy of pumping, water-level, and streamflow data. The model presented in this report is consistent with the conceptual model and hydrologic data of the area. The model uses a variably spaced grid so the model resolution is greatest near SWMUs, ground-water withdrawal wells, and dewatering facilities. The model will not provide accurate predictions on a scale smaller than the grid resolution.

The hydraulic-conductivity zones used in the model represent large-scale variations in hydraulic properties; the actual spatial variations of hydraulic properties of the aquifer system occur on a much smaller scale and are poorly defined. Additionally, the aquifer system, being karst in nature, has a wide range of measured hydraulic conductivity. Finally, evidence indicates that the aquifer system behaves anisotropically, but no measured values of the degree of anisotropy exist.

The model is calibrated to average annual conditions during 2002 and may not represent flow during seasonal extremes. Seasonal potentiometric maps (Robinson and others, 2005) and continuous water-level data (fig. 16) indicate some local seasonal shifts in flow directions in the upper part of the Crumpton Creek Basin. Similarly, ground-water gradients near the divide north of SWMU 10 may change seasonally.

The particle-tracking program, MODPATH, is based on advective transport of “water” particles and does not consider additional processes such as sorption, dispersion, and diffusion that would affect the travel times of a ground-water contaminant. Travel times also are directly related to assumptions about aquifer porosity. Since no measured values of porosity exist for the study area, the simulations use a uniform value of porosity for each layer as estimated from typical values for the lithologies of the layers. If porosity estimates are too high, travel times would be underestimated. If porosity estimates are too low, travel times would be overestimated.

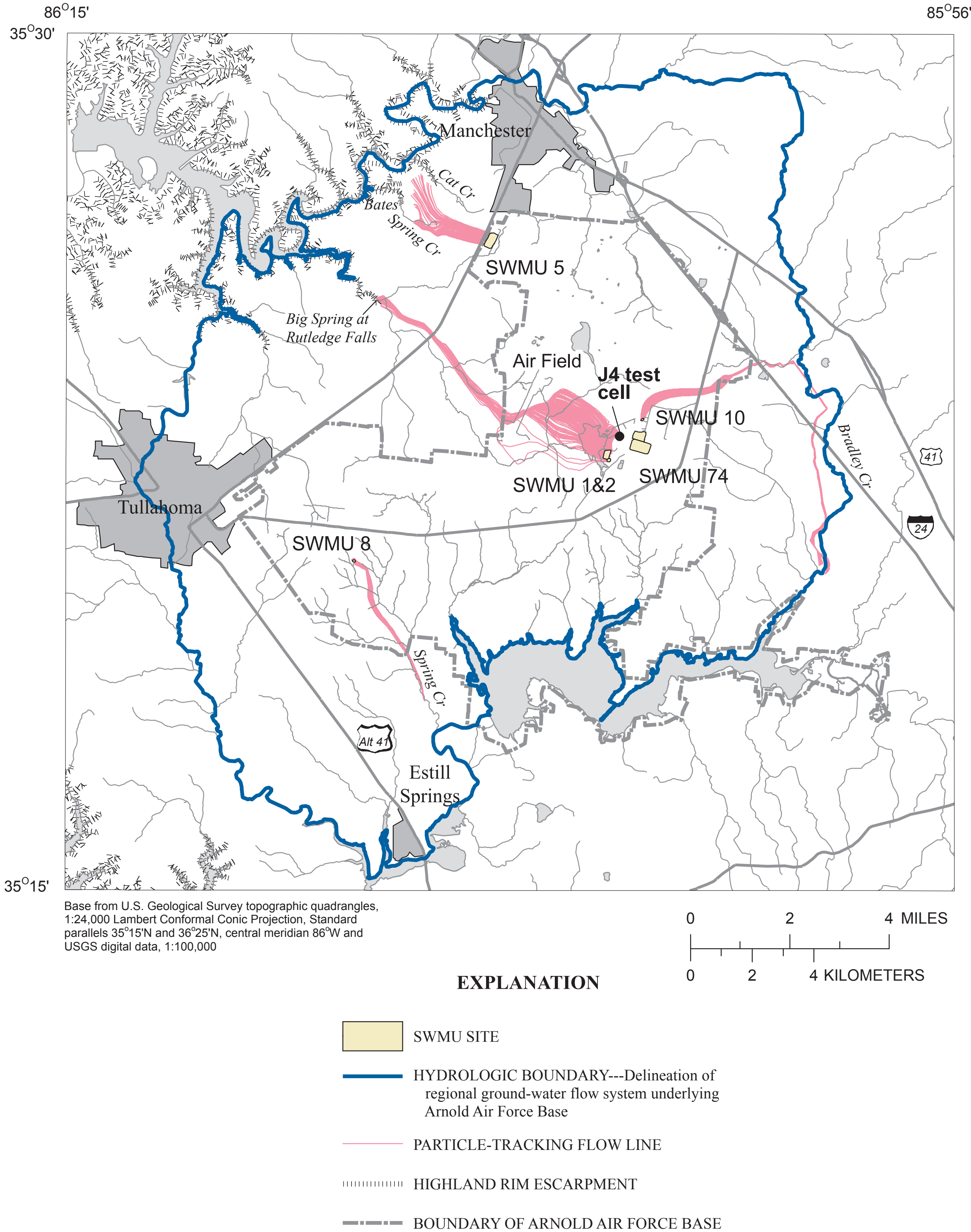


Figure 30. Forward particle tracking from SWMU 1&2, SWMU 5, SWMU 8, and SWMU 10 at Arnold Air Force Base with no ground-water withdrawal wells pumping.

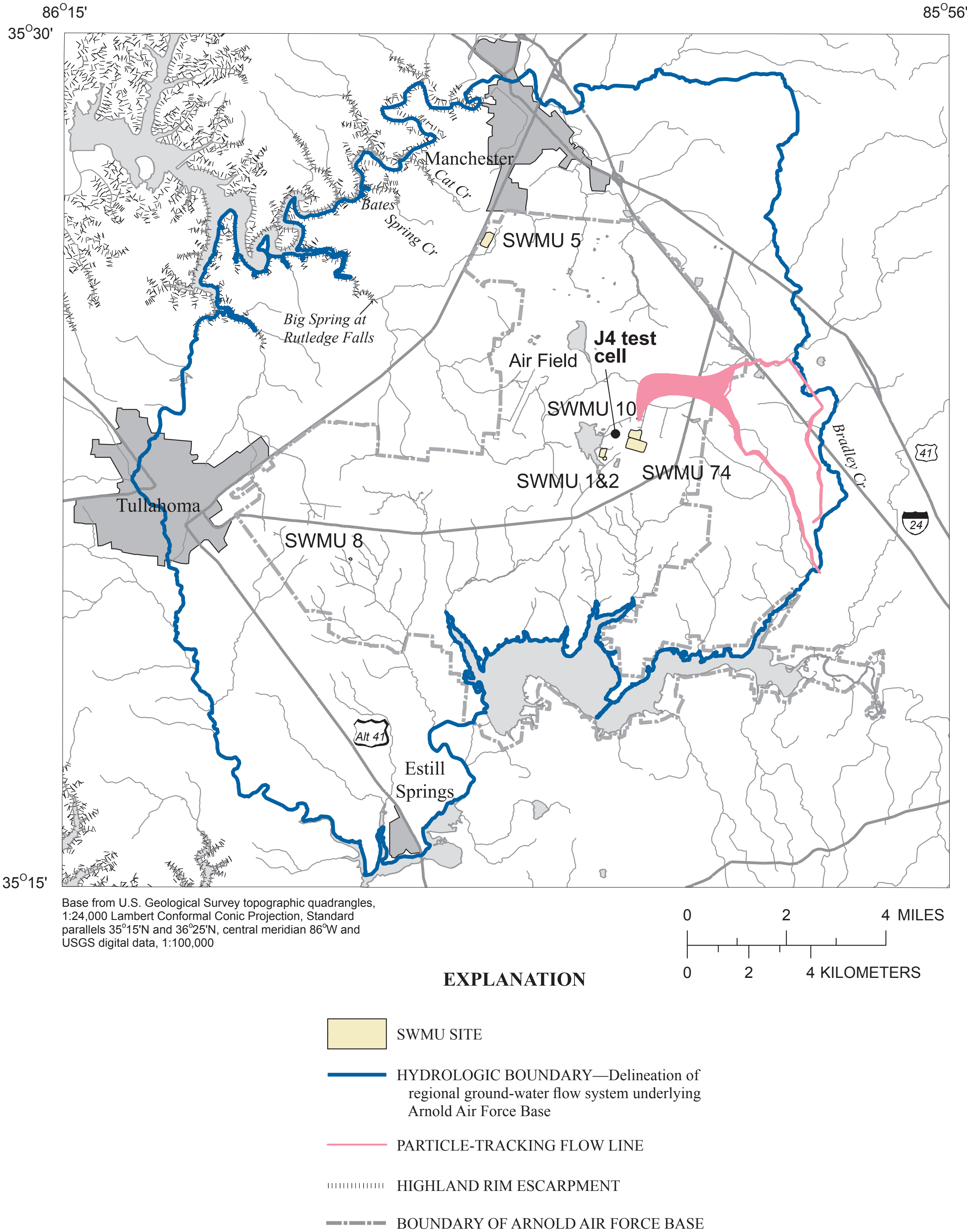


Figure 31. Forward particle tracking from SWMU 10 at Arnold Air Force Base under an alternative calibration of the flow model.

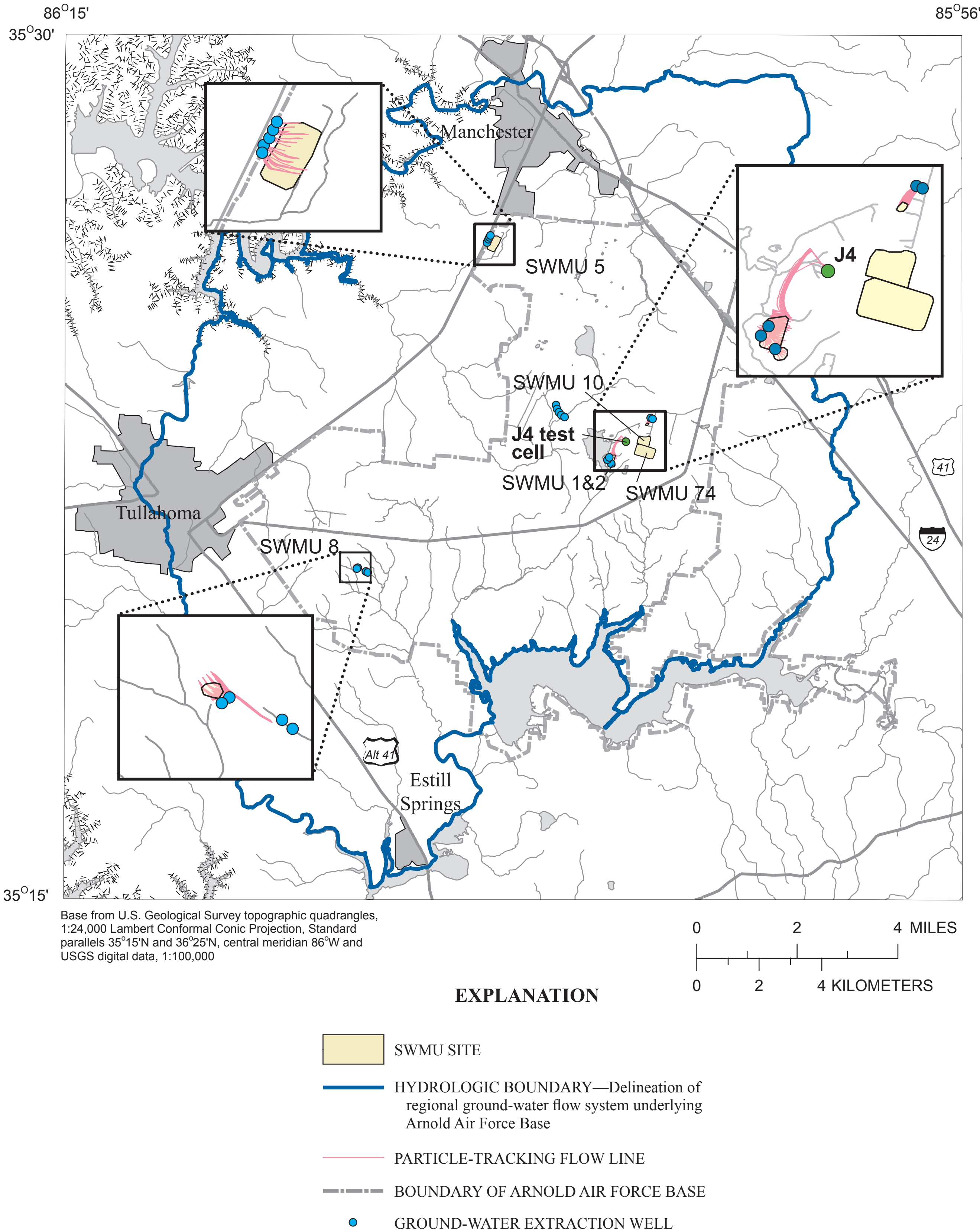


Figure 32. Forward particle tracking from SWMU 1&2, SWMU 5, SWMU 8, and SWMU 10 at Arnold Air Force Base with ground-water withdrawal wells pumping.

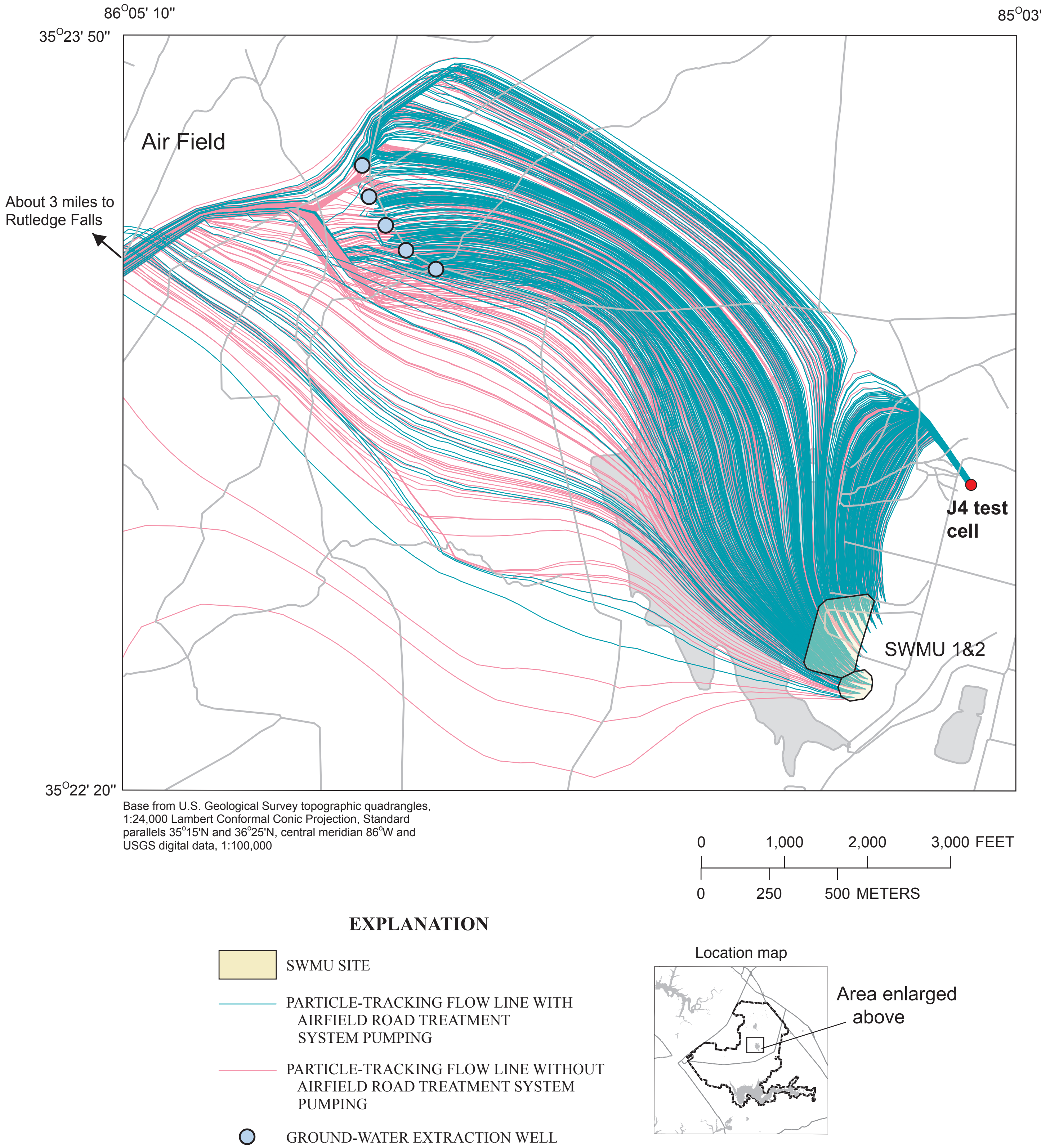


Figure 33. Forward particle tracking from SWMU 1&2 at Arnold Air Force Base with the airfield road ground-water withdrawal wells pumping.

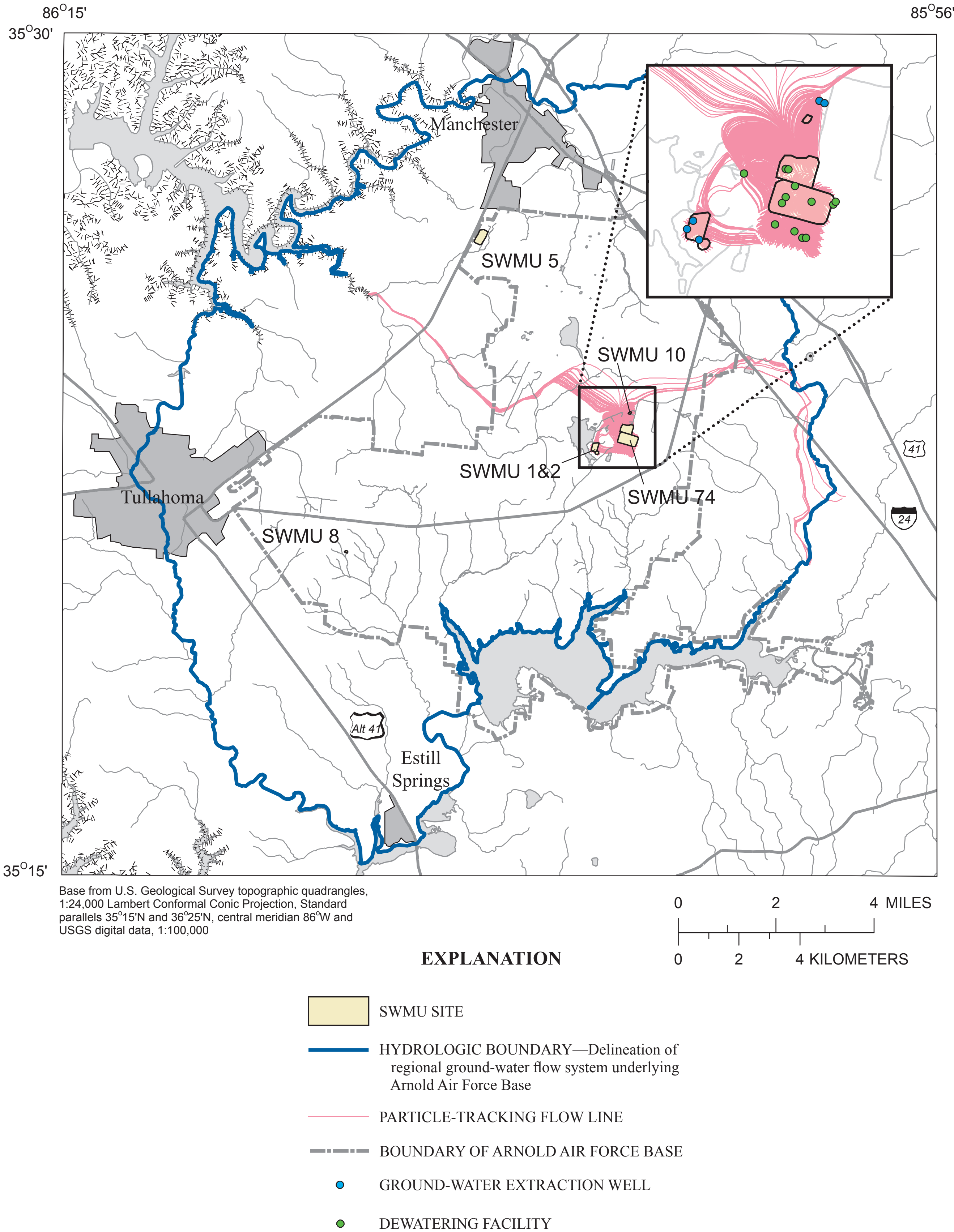
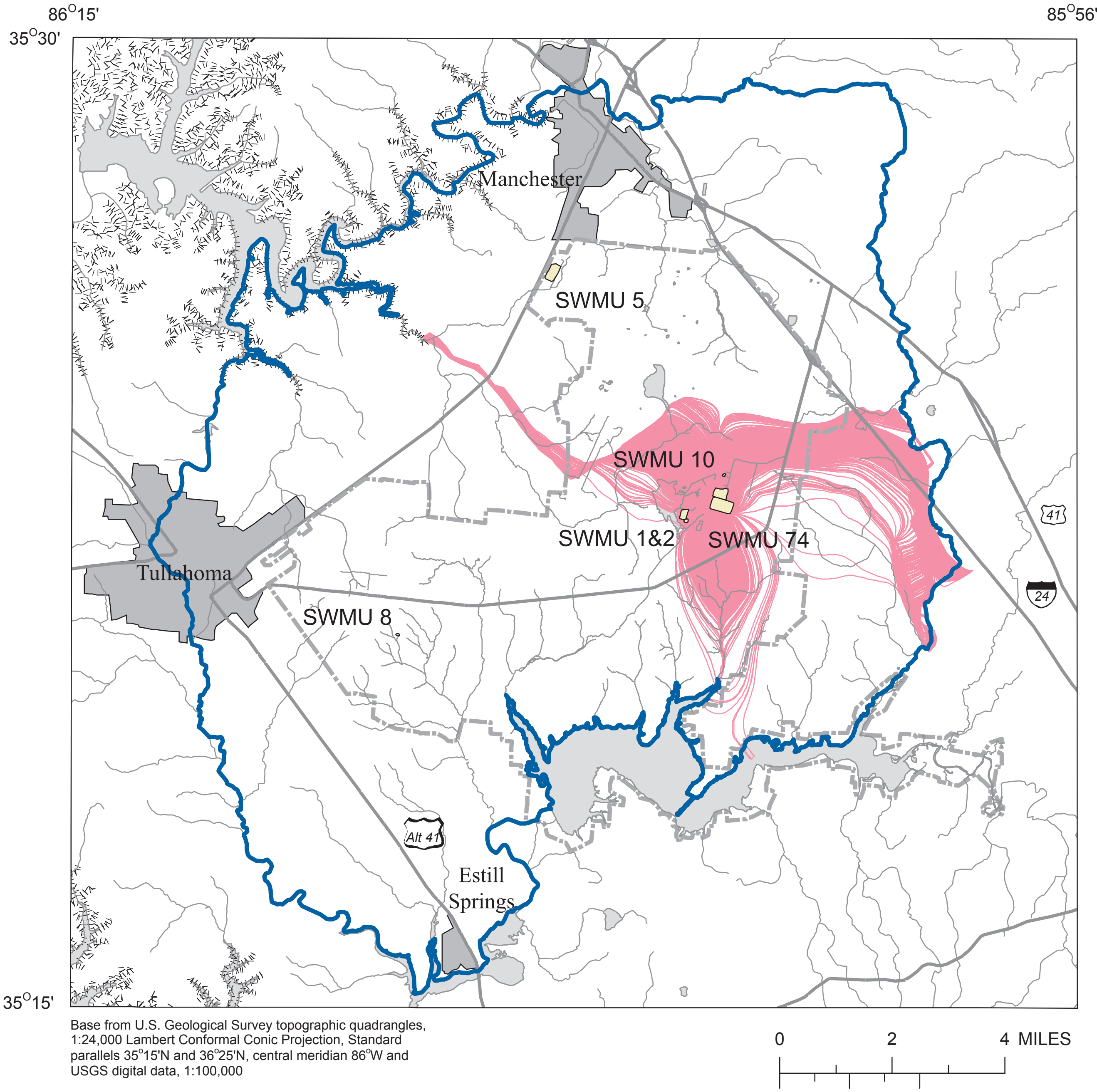


Figure 34. Forward particle tracking from the Main Test Area (SWMU 74) at Arnold Air Force Base with all dewatering facilities turned on.



EXPLANATION

SWMU SITE

HYDROLOGIC BOUNDARY—Delineation of regional ground-water flow system underlying Arnold Air Force Base

PARTICLE-TRACKING FLOW LINE

BOUNDARY OF ARNOLD AIR FORCE BASE

Figure 35. Forward particle tracking from the Main Test Area (SWMU 74) at Arnold Air Force Base with all dewatering facilities turned off.

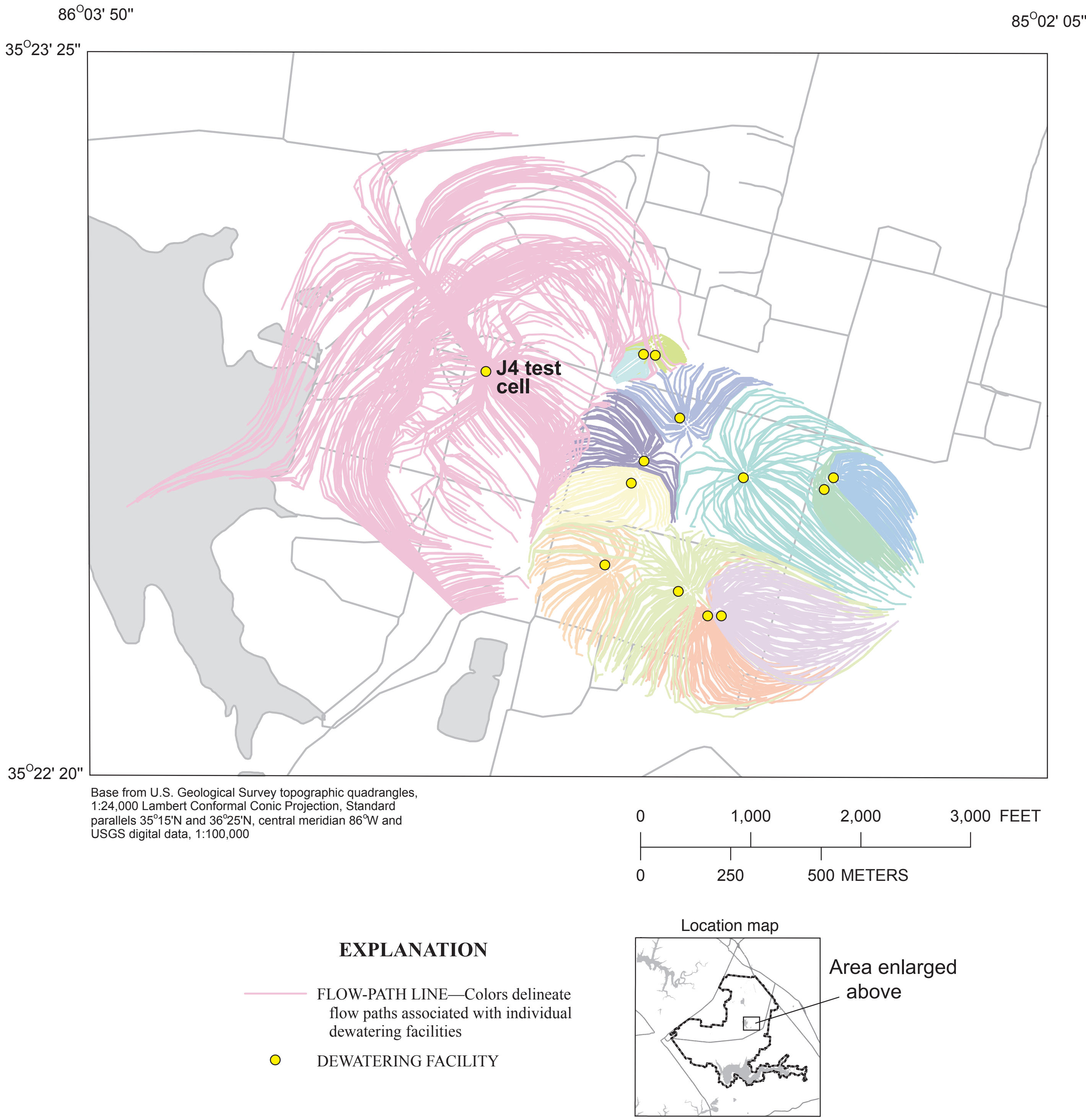


Figure 36. Backward particle tracking from dewatering facilities at the Main Test Area at Arnold Air Force Base.

Summary

Arnold Air Force Base (AAFB) occupies about 40,000 acres in Coffee and Franklin Counties, Tennessee. The primary mission of AAFB is to support the development of aerospace systems. Numerous site-specific ground-water contamination investigations have been conducted at designated Solid Waste Management Units (SWMUs) at AAFB. Several synthetic volatile organic compounds (VOCs), primarily chlorinated solvents, have been identified in the ground water at AAFB. Two ground-water contaminant plumes that originate at AAFB, the “SWMU 8 plume” and the “northwest plume,” have been shown to extend to regional discharge points outside the AAFB boundary.

The ground-water system at AAFB can be divided into several different zones or aquifers. The Manchester aquifer, the primary source of drinking water in the area, consists of chert gravels at the base of the regolith and solution openings in the upper part of the bedrock. A ground-water divide, approximately coinciding with the Duck River-Elk River surface-water divide, underlies AAFB and extends from southwest to northeast. Ground water flows from the divide area to the discharge areas, which are the major streams, springs, lakes, and reservoirs around the base. Several troughs are present in the potentiometric surface. The most prominent trough trends northwest to southeast in the Crumpton Creek Basin. The troughs in the potentiometric surface are believed to be associated with zones of high permeability within the aquifer that are important regional flow paths. These pathways share the following characteristics: a depression or trough in the bedrock surface, a trough in the ground-water surface, low gradients in the ground-water surface, and a large spring or group of springs at the downgradient end.

In the study area, recharge occurs from direct infiltration of precipitation throughout the study area. Based on water-budget and stream base-flow data, the AAFB study area can be divided into four areas with different recharge rates. The areas are: The Barrens area along the regional drainage divide; the Spring Creek, Dry Creek (at Estill Springs), and Taylor Creek Basins in the southwestern part of the study area; Sinking Pond; and the rest of the study area.

Ground water is withdrawn at numerous locations at AAFB for two primary reasons: ground-water withdrawal wells associated with ground-water contamination and dewatering activities around below-grade testing facilities. Ground-water withdrawal wells currently (2005) are operating at SWMU 1&2, SWMU 5, SWMU 8, and SMWU 10. Dewatering activities also occur at more than 20 facilities at AEDC.

The previous ground-water flow model (1992) was updated to incorporate new data and concepts about the ground-water flow system. For the computer flow model, the Highland Rim aquifer system was divided into four layers to simulate ground-water flow. The layers were defined on the basis of differences in physical characteristics that affect hydrologic properties. Model layer 1 corresponds to the shallow aquifer. Model layer 2 corresponds to the upper part of the Manchester aquifer. Model layer 3 corresponds to the lower part of the Manchester aquifer. Model layer 4 corresponds to the Fort Payne aquifer.

Model parameters (Harbaugh and others, 2000) were defined for recharge and hydraulic-conductivity zones. The digital model developed for this study was calibrated to steady-state conditions as defined by averaging measurements from spring and fall 2002. Overall, simulated water levels agree reasonably well with observed water levels. Water-level data at 615 wells were available for comparison to simulated conditions. The root mean square error for measured compared to simulated water levels was 9.8 feet. The average head difference between measured and simulated heads is –0.47 feet. The model has seven hydraulic-conductivity parameters with calibrated values that range from 0.2 to 6,500 feet per day. The model has four recharge parameters with calibrated rates of 4.2, 7.8, 17.7, and 110 inches per year (the high value represents focused recharge at Sinking Pond). The calibrated recharge rates correspond to an average recharge rate over the entire model area of 7.6 inches per year.

Particle-tracking flow paths were analyzed from selected SWMUs. From SWMU 1&2, most of the particles (70 percent) move to the northwest under the retention pond, then move west under the air field, then follow a prominent trough in the ground-water surface to discharge to Big Spring at Rutledge Falls. Pathlines from SWMU 5 show that particles generally move west and northwest to discharge to Cat Creek, Bates Spring Branch, or seeps and springs along the Highland Rim escarpment. Pathlines from SWMU 8 show that particles move to the southeast to discharge along Spring Creek. Pathlines from SWMU 10 show that particles move to the northeast before turning south to discharge to springs along the lower reach of Bradley Creek. Under an alternate calibration of the flow model, particles from SWMU 10 diverged to show two flow paths that both discharged to springs along the lower reach of Bradley Creek. Based on a detailed review of local water levels and water-quality data, this alternate scenario is believed to be less likely than the first one presented here, but may occur periodically or seasonally.

Currently (2005), ground-water withdrawal wells are operating at SWMU 1&2, SWMU 5, SWMU 8, and SWMU 10. Particle-tracking results from these SWMUs, under conditions with the ground-water withdrawal wells pumping, show that no particles leave the SWMUs. In 2005, five new ground-water withdrawal wells along the airfield road were scheduled to begin pumping to capture ground-water contamination that has already migrated beyond the SWMU 1&2 boundaries. The airfield road ground-water withdrawal wells and the J4 test cell capture about 89 percent of the particles from SWMU 1&2. About 11 percent of the particles under this simulation discharge near Rutledge Falls.

Three particle-tracking simulations were run to analyze the effects of dewatering facilities on flow paths in the Main Test Area (MTA). These simulations illustrate that the dewatering facilities have a substantial effect on flow paths

from the MTA and are effective in containing most of the ground water in this area.

The updated ground-water flow model is consistent with all current data on the ground-water system at AAFB. The model should provide a reliable tool to assist AAFB in managing the ground-water resources at the base.

Selected References

ACS, 2002, Changes in hydraulic parameters (determined from pumping tests) from source area to the head of the groundwater flow trough: FY 2002 Solid Waste Management Unit (SWMU 8) Site WP-6 Camp Forrest Water Treatment Plant Annual Interim Measure Operational and Effectiveness Monitoring Report for Arnold Air Force Base, TN, Draft Final, June 2002: Arnold Air Force Base, Tennessee, ACS.

ATA, 2004, Groundwater flow velocity estimate in bedrock based on correlation of GWTU down-times with well 577 contaminant trends: FY2004 Solid Waste Management Unit 8 (Site WP-6, former Camp Forrest Water Treatment Plant) Annual Interim Measure Operational and Effectiveness Monitoring Report for Arnold Air Force Base, Tennessee, Final, August 2004: Arnold Air Force Base, Tennessee, ATA.

Aycock, R.A., and Haugh, C.J., 2001, Ground-water hydrology and water-quality data for wells, springs, and surface-water sites in the Bradley-Brumalow Creeks area near Arnold Air Force Base, Tennessee, September to December 1999: U.S. Geological Survey Open-File Report 01-40, 49 p.

Battelle Columbus Division, 1988, Installation Restoration Program, Phase II-Conformation/Quantification, Stage 1, Final report, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee: Columbus, Ohio, Contract no. F33615–85–D–4507, Delivery order no. 12, July 1988, 7 sections.

Battelle Columbus Division, 1989a, Installation Restoration Program, RI/FS, Stage 2, Quality assurance project plan, Arnold Engineering Development Center, Arnold Air Force Base, Tennessee: Golden, Colorado, Contract no. F33615–85–D–4507, Task order no. 18, 2 sections.

Battelle Columbus Division, 1989b, Installation Restoration Program, RI/FS, Stage 2, Work plan, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee: Golden, Colorado, USAF Contract no. F33615–85–D–4507, Delivery order no. 18, 7 sections.

Battelle Denver Operations, 1989, Installation Restoration Program, RI/FS, Stage 2, Informal technical report—Field and analytical Data, Arnold Air Force Base, Tennessee: Golden, Colorado, Contract no. F33615–85–D–4507, Delivery order no. 26, 267 p.

Benham Group, 1989a, Base comprehensive plan, 65 Percent submittal, Arnold Air Force Base, Tennessee: Contract no. F40650–88–C0014, June 5, 1989, 16 plans.

Benham Group, 1989b, Executive summary—Plan overview, 65 Percent submittal, Arnold Air Force Base, Tennessee: Contract no. F40650–88–C0014, 6 sections, 1 appendix.

Brahana, J.V., and Bradley, M.W., 1986a, Preliminary delineation and description of the regional aquifers of Tennessee—The Highland Rim aquifer system: U.S. Geological Survey Water-Resources Investigations Report 82-4054, 38 p.

Brahana, J.V., and Bradley, M.W., 1986b, Preliminary delineation and description of the regional aquifers of Tennessee—The Central Basin aquifer system: U.S. Geological Survey Water-Resources Investigations Report 82-4002, 35 p.

Burchett, C.R., 1977, Water resources of the upper Duck River Basin, central Tennessee: Tennessee Division of Water Resources, Water Resources Series no. 12, 103 p.

Burchett, C.R., and Hollyday, E.F., 1974, Tennessee's newest aquifer [abs.]: Geological Society of America Abstracts with Programs, v. 6, no. 4, p. 338.

CH2M HILL, 1999, Resource conservation and recovery act facility investigation supplement for solid waste management unit 8 at Arnold Air Force Base: Oak Ridge, Tenn., CH2M HILL.

CH2M HILL, 2001, Resource conservation and recovery act facility investigation supplement for solid waste management unit 74 at Arnold Air Force Base: Oak Ridge, Tenn., CH2M HILL.

COLOG, 2002, HydroPhysical and geophysical logging results for solid waste management unit 10 at Arnold Air Force Base, Manchester, Tennessee: Golden, Colorado, COLOG.

Dames and Moore, 1975, Groundwater investigation and foundation study Aerospace-Jet Propulsion Systems Test Facility (ASTF): Technical report, unnumbered document, September 11, 1975, 40 p.

Engineering Science, 1984, Installation restoration program, Phase I: Records search, Arnold Engineering Development Center (AEDC), Tennessee: Atlanta, Georgia, Engineering Science, consultant engineer unnumbered document, October 1984, 6 sections.

Flohr, D.F., Garrett, J.W., Hamilton, J.T., and Phillips, T.D., 2003, Water resources data—Tennessee, water year 2002: U.S. Geological Survey Water-Data Report TN-02-1, 418 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, Prentice Hall, 604 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—user guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Haugh, C.J., 1996a, Hydrogeology of the area near the J4 test cell, Arnold Air Force Base, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 96-4182, 43 p.

Haugh, C.J., 1996b, Well-construction, water-level, and water-quality data for ground-water monitoring wells for the J4 hydrogeologic study, Arnold Air Force Base, Tennessee: U.S. Geological Survey Open-File Report 95-763, 81 p.

Haugh, C.J., and Mahoney, E.N., 1994, Hydrogeology and simulation of ground-water flow at Arnold Air Force Base, Coffee and Franklin Counties, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 93-4207, 69 p.

Haugh, C.J., Mahoney, E.N., and Robinson, J.A., 1992, Well-construction, water-level, geophysical, and water-quality data for ground-water monitoring wells for Arnold Air Force Base, Tennessee: U.S. Geological Survey Open-File Report 92-135, 88 p.

Heath, R.C., 1989, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Hill, M.C., 1998, Methods and guidelines for effective model calibration: with application to UCODE, a computer code for universal inverse modeling, and MODFLOWP, a computer code for inverse modeling with MODFLOW: U.S. Geological Survey Water-Resources Investigations Report 98-4005, 90 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—user guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 209 p.

Hoos, A.B., 1990, Recharge rates and aquifer hydraulic characteristics for selected drainage basins in Middle and East Tennessee: U.S. Geological Survey Water-Resources Investigations Report 90-4015, 34 p.

JAVA Corporation, 2000, Aerial thermography surveying—identification of potential springs phases II and III: Huntsville, Alabama, JAVA Corporation.

Mahoney, E.N., and Robinson, J.A., 1993, Altitude of the potentiometric surface in the Manchester aquifer at Arnold Air Force Base, May 1991, Coffee and Franklin Counties, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 93-4059, 1 sheet, scale 1:97,000.

McCabe, G.J., McLaughlin, J.D., and Muller, R.A., 1985, Thornwaite continuous monthly water budget: Louisiana Office of State Climatology, Climate Paper 85-1, 19 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 576 p. (586 p.)

Miller, R.A., 1974, The geologic history of Tennessee: Tennessee Division of Geology Bulletin 74, 63 p.

National Oceanic and Atmospheric Administration, 1960–2004, Climatological data annual summary, Tennessee: Asheville, N.C., National Climate Data Center, published annually.

Oak Ridge National Laboratory, 1989a, U.S. Air Force installation restoration program, phase IV, remedial design for site 10, Arnold Engineering Development Center, Tullahoma, Tennessee, Task 2.7, Baseline analytical report: Oak Ridge National Laboratory, Tennessee, Hazardous Waste Remedial Actions Program, August 1989, 6 sections, 5 appendices.

Oak Ridge National Laboratory, 1989b, U.S. Air Force installation restoration program, draft risk assessment for site 10, Arnold Engineering Development Center, Arnold Air Force Base, Tennessee: Hazardous Waste Remedial Actions Program unnumbered document, second draft, December 1989, 103 p.

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water-flow model: U.S. Geological Survey Open-File Report 94-464, 249 p.

Post, Buckley, Schuh and Jernigan, Inc., 1989a, Installation restoration program, Phase IV-A, Site 1 remedial action plan, v. 1, Arnold Air Force Base, Tennessee: Nashville, Tenn., Consultant engineer report, 6 sections, 3 appendices.

Post, Buckley, Schuh and Jernigan, Inc., 1989b, Installation restoration program, Phase IV-A, Site 1 remedial action plan, v. 2, Arnold Air Force Base, Tennessee: Nashville, Tenn., Consulting engineer report, 7 sections.

Post, Buckley, Schuh and Jernigan, Inc., 1989c, Installation restoration program, Phase IV-A, Site 1 remedial action plan, v. 3 (support documentation), Arnold Air Force Base, Tennessee: Nashville, Tenn., Consultant engineer report, 10 appendices.

Post, Buckley, Schuh and Jernigan, Inc., 1989d, Installation restoration program, Phase IV-A, Site 1, environmental assessment, Arnold Air Force Base, Tennessee: Nashville, Tenn., Consulting engineer report, 4 sections.

Post, Buckley, Schuh and Jernigan, Inc., 1989e, Draft work management plan for groundwater extraction investigation for site 1, Arnold Engineering Development Center: Nashville, Tenn., Consulting engineer report, 6 sections.

Robinson, J.A., and Haugh, C.J., 2004, Base-flow data in the Arnold Air Force Base area, Tennessee, June and October 2002: U.S. Geological Survey Open-File Report 2004-1318, 26 p.

Robinson, J.A., Hileman, G.E., and Haugh, C.J., 2005, Potentiometric surface of the Manchester Aquifer, Arnold Air Force Base, Tennessee, 2002: U.S. Geological Survey Scientific Investigations Map 2005-2882, 1 plate.

Rutledge, A.T., and Mesko, T.O., 1996, Estimated hydrologic characteristics of shallow aquifer systems in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces based on analysis of streamflow recession and base flow: U.S. Geological Survey Professional Paper 1422-B, 58 p.

Science Applications International Corporation, 1990, Installation restoration program, remedial investigation/feasibility study, stage 2, technical report draft, Arnold Air Force Base, Tennessee: Golden, Colo., Contract no. F33615–85–D–4543, task order no. 6, 3 v., 5 sections, 11 appendices.

U.S. Army Corps of Engineers, Mobile District, 1988a, Final foundation report, FY-89 PCD ANZY870198 Large Rocket Test Facility (J-6), Arnold Engineering Development Center, Air Force Systems Command, Arnold Air Force Station, Tennessee: U.S. Army Corps of Engineers, 94 p., 19 plates.

U.S. Army Corps of Engineers, Mobile District, 1988b, Final foundation report, FY-89 PCD ANZY870198 Large Rocket Test Facility (J-6), Appendix A, Arnold Engineering Development Center, Air Force Systems Command, Arnold Air Force Station, Tennessee: U.S. Army Corps of Engineers, 309 p.

Williams, S.D., 2003, Ground-water levels and water-quality data for wells in the Crumpton Creek area near Arnold Air Force Base, Tennessee, November 2001 to January 2002: U.S. Geological Survey Water-Resources Investigations Report 03-4175, 28 p.

Williams, S.D., and Aycock, R.A., 2001, Ground-water levels and water-quality data for wells in the Spring Creek area near Arnold Air Force Base, Tennessee, April and May 2000: U.S. Geological Survey Open-File Report 01-150, 16 p.

Williams, S.D., and Farmer, J.J., 2003, Volatile organic compound data from three karst springs in Middle Tennessee, February 2000 to May 2001: U.S. Geological Survey Open-File Report 03-355, 69 p.

Wilson, C.W., Jr., 1976, Geologic map and mineral resources summary of the Manchester quadrangle, Tennessee: Tennessee Division of Geology, MRS 86-NE, scale 1:24,000.

Wolfe, W.J., 1996, Hydrology and tree-distribution patterns of karst wetlands at Arnold Engineering Development Center, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 96-4277, 46 p.

Wolfe, W.J., Evans, J.P., McCarthy, Sarah, Gain, W.S., and Bryan, B.A., 2004, Tree-regeneration and mortality patterns and hydrologic change in a forested karst wetland—Sinking Pond, Arnold Air Force Base, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 03-4217, 53 p.

Wolfe, W.J., and League, D.E., 1996, Water-surface elevations of wetlands and nearby wells at Arnold Air Force Base, near Manchester, Tennessee: U.S. Geological Survey Open-File Report 95-753, 19 p.

Wolock, D.M., 2003a, Base-flow index grid for the conterminous United States: U.S. Geological Survey Open-File Report 03-263, digital dataset, accessed May 22, 2006, at *http://water.usgs.gov/lookup/getspatial?bfi48grd*

Wolock, D.M., 2003b, Flow characteristics at U.S. Geological Survey streamgages in the conterminous United States: U.S. Geological Survey Open-File Report 03-146, digital dataset, accessed May 22, 2006, at *http://water.usgs.gov/lookup/getspatial?qsitesdd*

Wolock, D.M., 2003c, Estimated mean annual natural groundwater recharge in the conterminous United States: U.S. Geological Survey Open-File Report 03-111, digital dataset, accessed May 22, 2006, at *http://water.usgs.gov/lookup/getspatial?rech48grd*

Woodward-Clyde Consultants, 1990, Ground water extraction investigation report, Hazardous waste site No. 1, Arnold Engineering Development Center, Arnold Air Force Base, Tullahoma, Tennessee: Consulting engineer report, September 28, 1990, 7 sections, 7 appendices.